

SHOCKS IN DENSE CLOUDS IN THE VELA SUPERNOVA REMNANT

- FUSE

NASA Grant NAG5-9002

Final Report

For the Period 1 March 2000 through 28 February 2002

Principal Investigator
Dr. Joy Nichols

March 2002

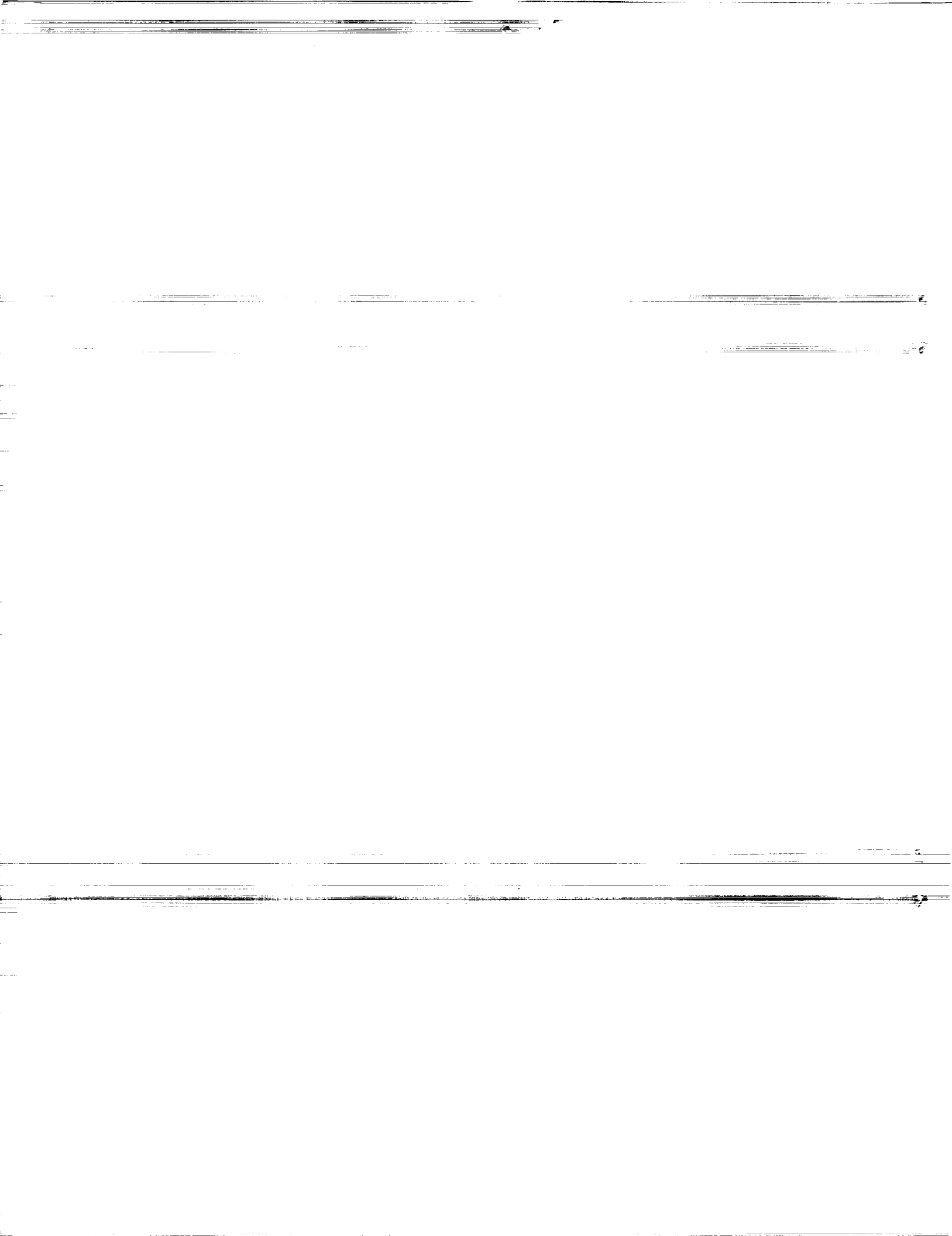
Prepared for:

National Aeronautics and Space Administration
Goddard Space Flight Center
Greenbelt, Maryland 20771

Smithsonian Institution
Astrophysical Observatory
Cambridge, Massachusetts 02138

The Smithsonian Astrophysical Observatory
is a member of the
Harvard-Smithsonian Center for Astrophysics

The NASA Technical Officer for this grant is George Sonneborn, 681.0, National Aeronautics and Space Administration, Goddard Space Flight Center, Greenbelt, Maryland 20771.



1. Summary

We have obtained 8 LWRs *FUSE* spectra to study a recently identified interaction of the Vela supernova remnant with a dense cloud region along its western edge. The goal is to quantify the temperature, ionization, density, and abundance characteristics associated with this shock/dense cloud interface by means of UV absorption line studies. Our detection of high-velocity absorption line C I at +90 to +130 km/s with IUE toward a narrow region interior to the Vela SNR strongly suggests the Vela supernova remnant is interacting with a dense ISM or molecular cloud. The shock/dense cloud interface is suggested by (1) the rarity of detection of high-velocity C I seen in IUE spectra, (2) its very limited spatial distribution in the remnant, and (3) a marked decrease in X-ray emission in the region immediately west of the position of these stars where one also finds a 100 micron emission ridge in IRAS images. We have investigated the shock physics and general properties of this interaction region through a focussed UV absorption line study using *FUSE* spectra.

We have *FUSE* data on OVI absorption lines observed toward 8 stars (Table 1) behind the Vela supernova remnant (SNR). We compare the OVI observations with IUE observations of CIV absorption toward the same stars (Nichols & Slavin 2002). Most of the stars, which are all B stars, have complex continua making the extraction of absorption lines difficult. Three of the stars, HD 72088, HD 72089 and HD 72350, however, are rapid rotators ($v \sin i > 100 \text{ km s}^{-1}$) making the derivation of absorption column densities much easier. We have measured OVI and CIV column densities for the “main component” (i.e. the low velocity component) for these stars. In addition, by removing the H_2 line at 1032.35 \AA (121.6 km s^{-1} relative to OVI), we find high velocity components of OVI at $\sim 150 \text{ km s}^{-1}$ that we attribute to the shock in the Vela SNR. The column density ratios and magnitudes are compared to both steady shock models and results of hydrodynamical SNR modeling. We find that the models require the shock to be relatively slow ($\sim 100 - 170 \text{ km}$

s^{-1}) to match the FUSE data. We discuss the implications of our results for models of the evolution of the Vela SNR.

Table 1. Stars Observed in the Vela SNR Region

Star	III	b II	Spec. Type	distance (hip)	distance (sp)	exp. time
HD 71019	260.37	-3.14	B3 II/III			4066.
HD 71336	261.01	-3.21	B3 III/IV			2190.
HD 72179	262.08	-2.97	B4 II/III	640		1419.
HD 72088	262.67	-3.49	B3 III/IV	1630:		52327.
HD 72089	263.21	-3.89	B5 II/III	1600:		2280.
HD 72350	262.71	-3.19	B4 IV	390	685	806.
HD 72648	262.23	-2.48	B1/B2 Ib	1340	741	5204.
HD 74662	266.90	-3.63	B3 V	1060:		4812.

2. Vela Supernova Remnant – Observation History

The Vela supernova remnant (SNR) has proven to be quite useful for improving our understanding of shock physics and ionization in evolved SNRs. This remnant’s large angular size (~ 8 degrees) and relative proximity (500 pc or less) have made it an active target for SNR studies at many wavelengths – sometimes with dramatic results; e.g., the large-scale X-ray ejecta “bullets” found by Aschenbach et al. (1995). The large number of background early type stars towards Vela have also allowed more extensive absorption line studies in the optical and UV than for any other galactic remnant (Jenkins & Wallerstein 1995 and references therein). The goal of this proposal was to obtain high resolution FUSE spectra of several background stars known to show high-velocity absorptions in order to investigate the nature of a narrow region producing peculiar high-velocity C I features, strongly suggestive of shocks in dense or molecular clouds. From these *FUSE* data, we

are mapping out the densities, temperatures, abundances, and ionization structure of the SNR/cloud interaction using several unique atomic and molecular diagnostics available only in the 900-1150 Å wavelength range.

Previous UV absorption lines studies of early-type stars behind the Vela SNR have shown this technique to be a very sensitive probe of the kinematics, densities, and abundances occurring in the cooling regions behind the SNR's main shock front. For example, Jenkins, Wallerstein, & Silk (1984) found -90 km/s to $+180$ km/s velocity components in about 1/3rd of 45 stars they studied with IUE data. Their analysis showed apparently chaotic kinematics (i.e., no strong geometric expansion effects), lower depletion than normal ISM (presumably due to shock grain destruction), and some relatively strong lines of C I, – but not at high velocity. Jenkins & Wallerstein (1995) using GHRS spectra, however, did find 6 high-velocity C I components in the spectrum of one star located behind Vela (HD 72089) and concluded this represented cooled and recombined gas behind the shock wave. Jenkins & Wallerstein estimated $1000 \leq n_H \leq 2900$ cm $^{-3}$ and a dynamic pressure of $2-4 \times 10^{-9}$ dyn cm $^{-2}$. The pre-shock value n_0 was estimated at 13 cm $^{-3}$ suggestive of a relatively dense ISM cloud.

The high density and high pressure detected towards this one star turns out not to be an isolated or small scale phenomenon. I have analyzed high-dispersion IUE NEWSIPS spectra for 74 stars in the VELA region and find many more high-velocity absorption features than previously reported. A particularly interesting result from this work is the clear detection of high-velocity (i.e., $+90$ to $+130$ km/s) C I (1277,1328,1560,1656 Å) toward 11 of these stars, most of which lie projected into a narrow N-S region in the remnant (see Figure 1). Detection of high-velocity C I at IUE's spectral resolution ($V \geq 25$ km/s) is extremely rare. Of the 800 O and B star spectra that we have previously analyzed for various projects (including other SNRs; Nichols-Bohlin and Fesen 1986,1990,1993), only

4 stars outside Vela showed any high-velocity C I absorption^{4,5}.

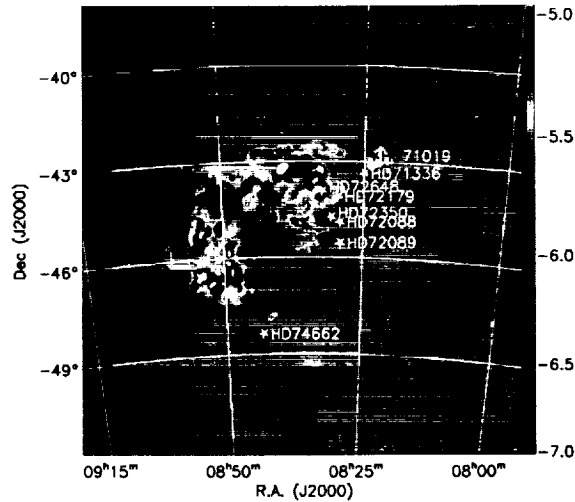


Figure 1: ROSAT X-ray image of Vela SNR (Aschenbach et al. 1995). The positions of the stars observed with FUSE have been plotted on the image.

A ROSAT PSPC X-ray image of the Vela SNR (Aschenbach et al. 1995) shows the western region to be relatively dim in low energy X-rays, consistent with some attenuation ($N(H) \geq 10^{21} \text{ cm}^{-2}$). Most of the stars in which we detected strong high-velocity C I are projected along a rather narrow “band” running from north to south through the interior of the projected SNR (see Figure 1). This band is approximately 1 degree in breadth and lies along the boundary between the X-ray bright interior of the SNR and the western X-ray faint region, with a projected length of about 30 pc (if $d = 500$ pc). This correlation between high velocity C I and the X-ray boundary suggests a physical association with the SNR and the cloud interface attenuating the X-ray emission.

3. High Ions as Tracers of SNR Evolution

Supernova remnants have been observed in a variety of ways in wavelength bands ranging from the radio to X-rays. Each of these bands reveals unique information about the SNR. For example, the X-rays give us information about the hot gas at the shock front and in the interior of the remnant, while optical emission comes from warm gas either being heated by the shock or cooling in the post-shock region. Recently, as the capability to observe remnants in the UV has improved both emission and absorption from shocks in SNRs has been observed.

Shocks in middle-aged remnants (defined as SNRs that have recently or are in the process of going radiative) are typically $\sim 100 - 400 \text{ km s}^{-1}$. These speeds imply temperatures in the shocks of $T \sim 10^5 - 10^6 \text{ K}$, which is characteristic of emission in the UV. Thus observations of emission lines in such shocks are important diagnostics. Absorption line observations in the UV also offer the possibility of deriving decisive information on the nature of the shocks since the same ions that radiate in the UV often have strong absorption lines as well. Absorption line observations in the spectra of bright objects behind remnants have the advantage that they are not affected by self-absorption and scattering in the shock as are emission line observations. In addition, absorption line observations can be sensitive to much smaller column densities than emission line observations.

The strong UV resonant absorption lines of high ionization stages of abundant elements, namely C IV, N V, Si IV and O VI, have been detected widely in both the Galactic plane and halo. A variety of theories have been put forward to explain the existence and distribution of these ions in the ISM. Most of these models involve the interaction of the hot phase of the ISM with cooler phases. In many cases, particularly for long lines of sight, the observed column density ratios have not been consistent with any single model and so have been explained as due to a combination of sources such as evaporating clouds, turbulent

mixing layers and shocks. This has been somewhat dissatisfying, however, since we have lacked good examples of individual objects with which the absorption could be clearly associated. In particular we have lacked a clear association of high ion absorption with a known supernova remnant which could serve as a check on shock models for the high ions. Recent observations of emission from the high ions using *HUT* and *FUSE* provide valuable information on the shocks but are limited to relatively bright regions of the brightest evolved SNRs. In addition, emission line intensities depend on the electron density and temperature in the shock in addition to the high ion column density. As a result interpretation of such observations is more model dependent than the more direct observation of the high ion column density. A potentially very powerful method of gaining information on the nature of SNR shocks is to combine emission and absorption observations of the high ion UV lines.

4. *FUSE* Observations and Data Processing

We have obtained data from *FUSE* observations of eight stars behind (or nearly behind in one case) the Vela SNR (proposal no. A129, Joy Nichols, PI). The observations were carried out in early 2000 except for HD 72350 which was observed in May 2001. Table 1 gives the names, positions, spectral types, distances and total exposure times for the stars. We have reprocessed the data, originally processed with an earlier version of the CalFUSE processing software, with the most recent version, 2.0.5. The reprocessed data show a much more consistent wavelength calibration and reduced noise compared with the original processing. In some cases the detector alignment was such that the detector 2 was not illuminated by the source and is thus not usable. In all cases the source was centered in the LWRS (low resolution aperture) of the LiF1 spectrograph channel. In the spectra we present we have combined all the exposures within a given detector segment by doing an exposure time weighted average for the flux. The flux errors have been added in quadrature

(since they are statistically independent) to derive the errors for the combined exposures. We have tested whether it was necessary to apply pixel shifts when adding exposures in the way recommended in the *FUSE Data Analysis Cookbook* but have found little difference in the spectra produced with and without the pixel shifts.

5. Stellar Continua and Rotation Speed

Our primary interest in this investigation is the nature of the Vela supernova remnant (SNR) as revealed by the UV absorption line data. In particular we are interested in the O VI absorption due to gas shocked by the SNR blastwave. The stars available behind Vela, however, are mostly far from optimal for such investigations. There are only a few O stars behind Vela and all of the stars in our sample are B stars. These stars generally have complex continua making extraction of accurate absorption lines difficult if not impossible. The situation is much improved when a B star is a rapid rotator. In that case the continuum features are blended together and broadened and determination of absorption line parameters becomes relatively straightforward. It is generally not obvious from inspection of the spectrum, however, whether a given star is a rapid rotator or not and thus whether spectral features are interstellar or photospheric in origin. We assess the rotation speed in our stars by comparison of the observed spectra to model spectra (J. Aufdenberg, private communication), particularly the C III 1175Å line. The 1175Å line is very useful in this respect because, as an absorption line from an excited state with a high excitation energy, it is unambiguously photospheric in origin. Moreover it is a multiplet of several closely spaced lines which are blended only if there is a high rotational velocity. Using stellar models then, we are able to determine the $v \sin i$ for the stars and thus gain a much clearer understanding of the nature of the stellar continuum. It should be noted, however, that the model continua, even for the rapid rotators, do not closely

match the observed continua and so we are unable to use them for the purposes of fitting the absorption lines. Instead we limit our attempts at absorption line fitting to the rapid rotators and in these cases assume a smooth (low order polynomial) continuum. Using these techniques we have determined that three of our stars, HD 72088, HD 72089 and HD 72350 are rapid rotators with $v \sin i \gtrsim 100 \text{ km s}^{-1}$. Figure 2 compares the C IV and O VI spectral regions for these three stars.

6. H₂ Removal and O VI Fitting

FUSE is an excellent instrument for observing H₂ in the interstellar medium with access to dozens of lines within its bandpass. This abundance of H₂ lines, however, becomes a hindrance when one is attempting to analyze the absorption lines of other species. The O VI line at 1031.93Å is in a wavelength region relatively clear of H₂ lines. A line that is strong in several of our spectra, however, is the Lyman band R(4)(6-0) line at 1032.35Å at a displacement of 121.6 km s⁻¹ relative to the O VI 1032 line. This displacement puts the H₂ line very close to where we expect to find O VI absorption from the Vela SNR shock. Thus we are interested in attempting to remove the H₂ line to see if there is any O VI absorption underneath.

The technique we have developed is straightforward. We find another H₂ absorption line originating in the same vibration-rotation state (i.e. $v = 0$, $J = 4$) located in a fairly smooth part of the continuum. We have used the P(4)(6-0) line at 1035.18Å and the R(4)(5-0) line at 1044.54Å. For these lines we have fit the surrounding continuum with a low order (5 or less) Legendre polynomial and from this determined the apparent optical depth as a function of velocity, $\tau_a(v)$. Multiplying by the ratio of oscillator strength-wavelength products, $\lambda_1 f_1 / \lambda_2 f_2$, we then derive the apparent optical depth for the 1032.35Å line. We then fit the continuum surrounding the 1032.35Å line and finally get the “H₂ cleaned”,

normalized spectrum by multiplying the normalized spectrum by $\exp(-\tau_a(v))$. This procedure clearly introduces errors at each step and we have been careful to propagate the errors properly. This work is in the final stages.

7. Comparison with Model Predictions

In order to gain insight into the observational results, the Vela SNR evolution was modelled using Piecewise Parabolic Method numerical hydrodynamics code. The code is 1-D and incorporates non-equilibrium ionization, radiative cooling, thermal conduction and magnetic pressure.

The initial runs were made using the O VI and C IV data for 3 stars in the western region of the Vela SNR, assuming a uniform ambient medium. The result, after constraining the size and shock speed to known values, was unusually low explosion energy. This inconsistency can be overcome by assuming the supernova goes off in a cavity created by the progenitor.

Figures 3-5 present the temperature, velocity, and density profiles from the model runs. Some of the complexity of the hydrodynamics of the transition from adiabatic to radiative can be readily seen. As the shock slows enough that radiative cooling causes the post-shock gas to cool to $T \sim 10^4 \text{K}$, the shock loses pressure support and slows. The hot gas behind the shock then catches up with the shock, giving the shock renewed acceleration and resulting in extra compression and cooling in the cool shell. A reverse shock is initiated and propagates back into the hot gas then setting up the reverse shock/contact-discontinuity/forward shock structure familiar from situations in which a shock encounters a higher density medium such as a cloud. In this case it results simply from the dynamics of the transition to a radiative remnant. Note especially that after cooling sets in the hot gas in the remnant has

a substantially higher velocity than the gas in the radiative forward shock.

Figure 6 shows the predictions of the numerical hydrodynamic models for the ratio O VI/C IV vs. shock speed. Also plotted are the results of steady radiative shock models kindly provided by John Raymond. The differences between the model results are clearly very large and point to the importance of dynamics in our calculations. A large contributor to the differences is the hot gas inside the remnant that constitutes the sole source of the O VI after the shock has slowed below the speed needed to produce O VI. Another factor is the contribution of the reverse shock to the C IV column, which becomes dominant for shock speeds below ~ 120 .

Further complications for comparison of observational data to models is demonstrated by Figure 7 which shows the C IV 1548 Å and O VI 1032 Å absorption profiles calculated for a 4×10^4 yr after the SN explosion. O VI, coming primarily from hot gas in the remnant, has a single component centered at about 120. C IV, on the other hand, comes from both the forward shock and a thin layer on both sides of the reverse shock; thus it has two components. The extremely different nature of the absorption components for C IV and O VI cautions us against any simple component matching analysis of the observational data.

8. Conclusions

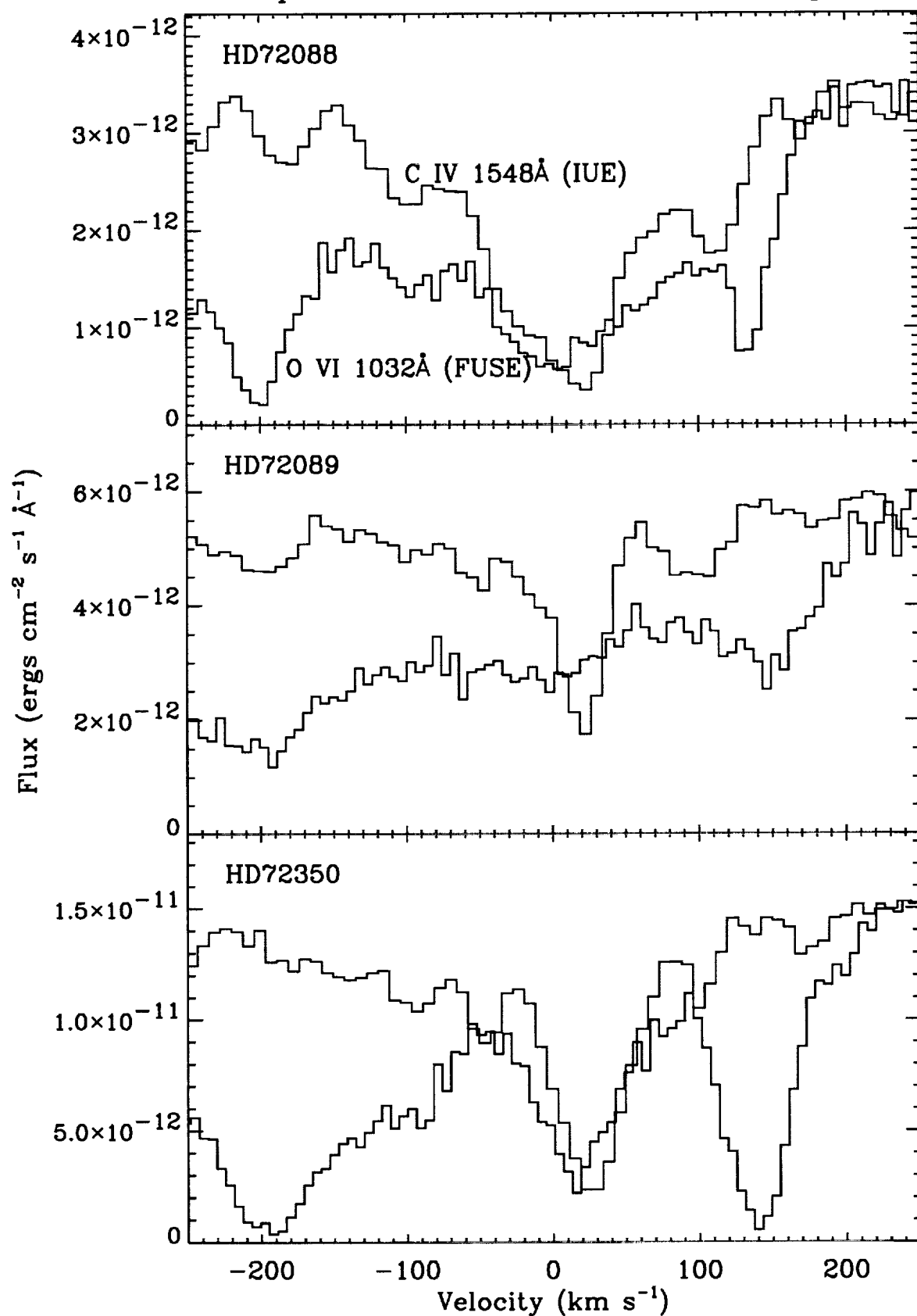
- 1. C IV and O VI absorption line observations can be powerful diagnostics of SNR characteristics: shock speed, ambient density, age - but interpretation of such results requires careful comparison with detailed models.
- 2. Steady radiative shock and fully time dependent SNR evolutionary calculations differ markedly in their predictions of C IV and O VI column densities vs. shock speed. This is primarily due to the presence of secondary shocks in the cold shell

caused by the dynamics of shell formation and the presence of hot gas behind the cold shell in the SNR bubble.

- 3. Column densities for O VI and C IV compared to both steady shock models and hydrodynamical SNR modeling, require the shock to be relatively slow ($\sim 100\text{--}170$) to match the data.

Figure 2

FUSE/IUE Data for Vela SNR Stars
Comparison of O VI and C IV Absorption



Velocity Profile Evolution of a Supernova Remnant

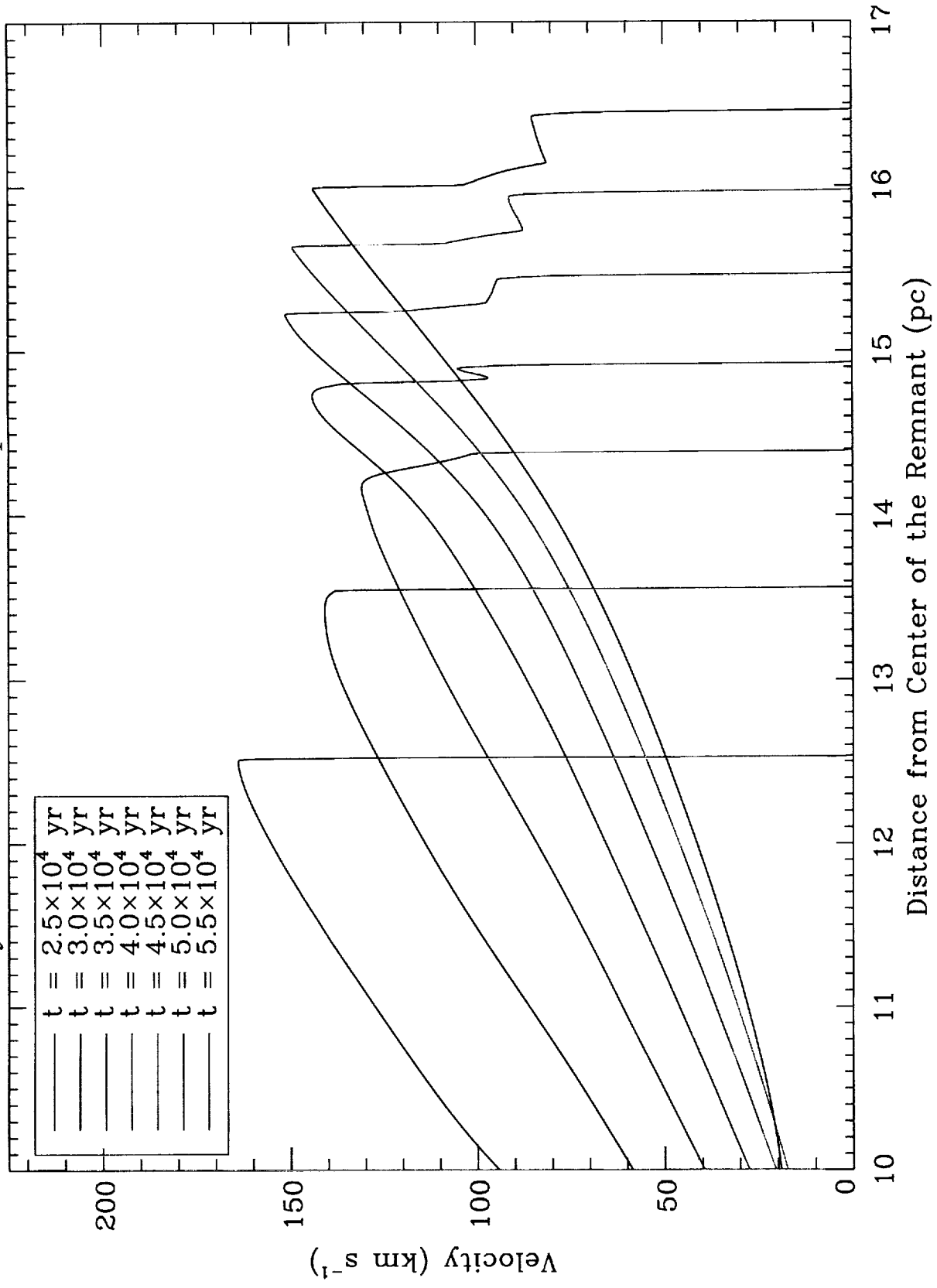


Figure 3

Temperature Profile Evolution of a Supernova Remnant

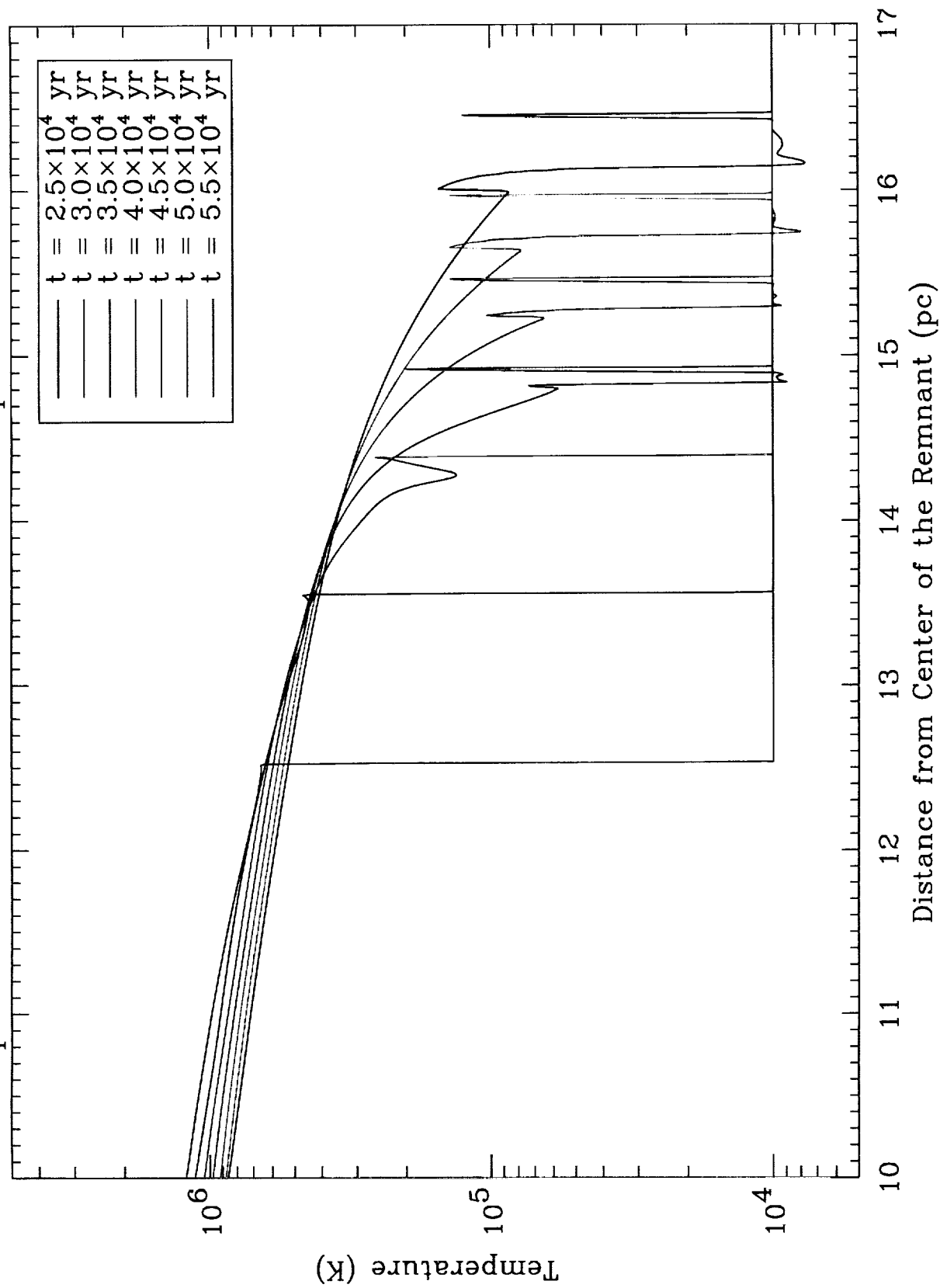


FIGURE 4

Density Profile Evolution of a Supernova Remnant

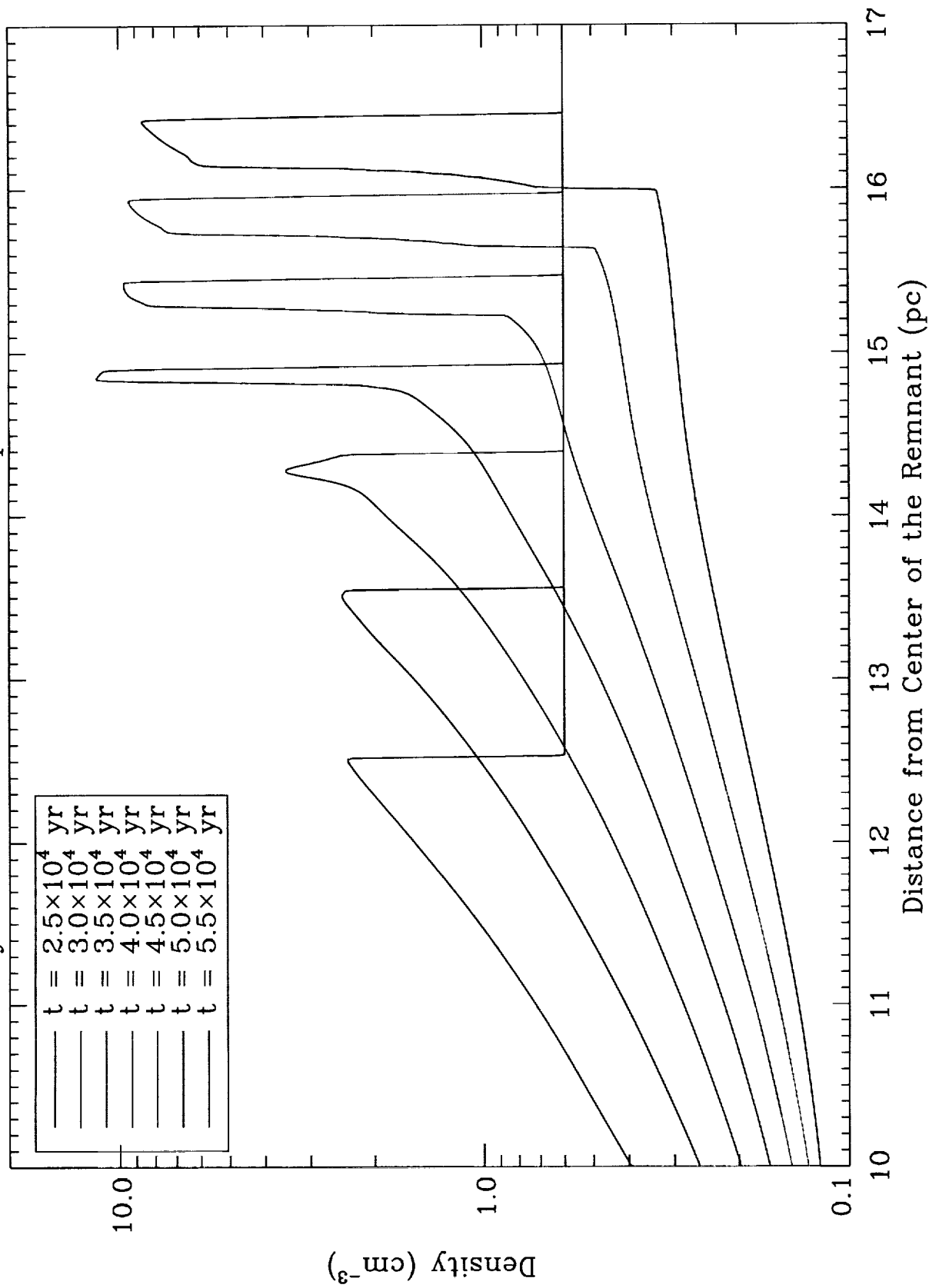


Figure 5

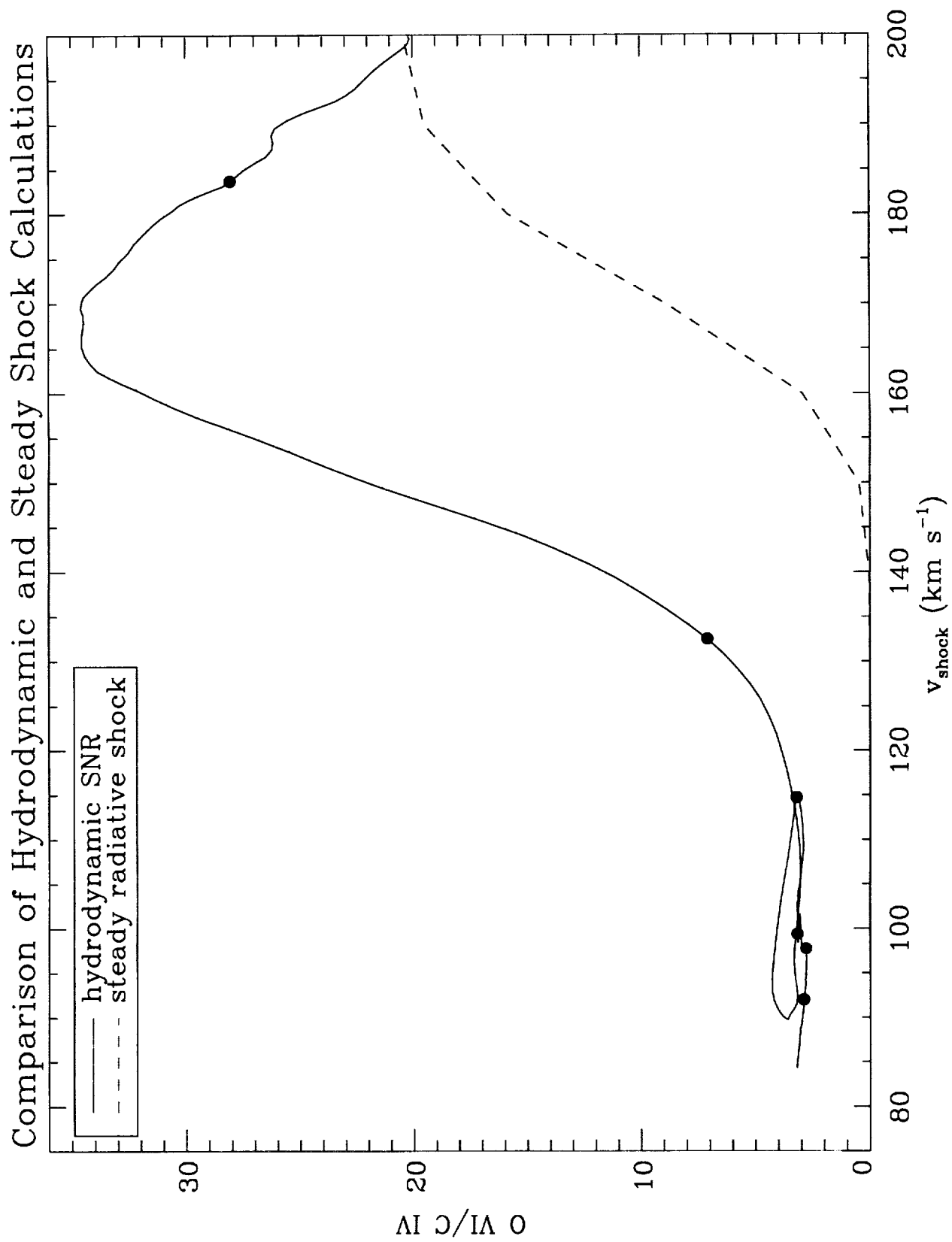


Figure 6

Example of Calculated C IV and O VI Absorption Profiles

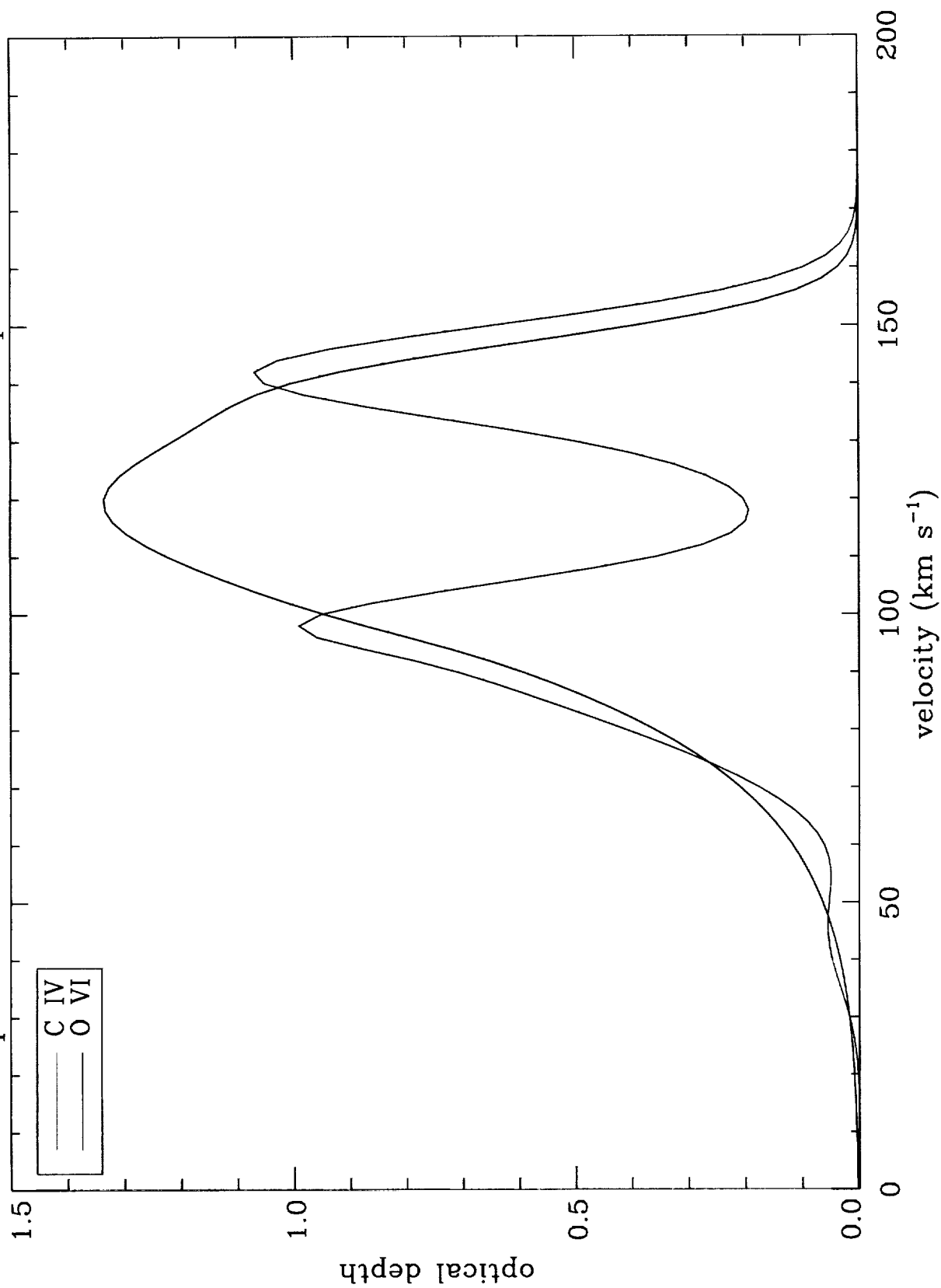


Figure 7

2
Fig. 1. *FUSE* data for the 1032Å line of O VI (red) and *IUE* data for the 1548Å line of CIV (green) for the three rapidly rotating stars in our *FUSE* dataset. Some or all of the absorption at $\sim 120 \text{ km s}^{-1}$ and $\sim 200 \text{ km s}^{-1}$ in the *FUSE* spectra is due to H₂. The *FUSE* data have been binned by a factor of three to increase signal-to-noise.

3
Fig. 2. Evolution of the velocity profile in a supernova remnant in our calculation in which we attempt to simulate the Vela SNR. The legend indicates the time after the SN explosion for which each profile corresponds. Note how after $4.0 \times 10^4 \text{ yr}$ when the cold shell has formed, the fastest moving gas is interior to the shock at the location of the reverse shock. At these times this hot gas interior to the shell, which contains O VI, may have a velocity larger than the outer shock speed.

4
Fig. 3. Same as Fig. 2. but the temperature. Note the formation of the cool shell, the thin radiative outer shock and the reverse shock that forms between $t = 3.5 \times 10^4 \text{ yr}$ and $4.0 \times 10^4 \text{ yr}$ after the explosion.

5
Fig. 4. Same as Fig. 2. but the density. After formation the cool shell expands over time. The dense cold part of the shell is just behind the forward shock. The contact discontinuity can be seen best in the last profile where the density begins to drop behind the outer shock, flattens somewhat then drops again sharply at the inner (reverse) shock.

6
Fig. 5. Ion column density ratio vs. shock speed. Here the large differences between the steady shock and hydrodynamical results are demonstrated. The colored dots correspond to the times on Figs. 2-4. The loop in the curve is due to the slowing of the shock after going radiative and subsequent re-acceleration after the hot gas in the expanding bubble catches up with the shock.

Fig. 4.--Absorption profiles for O VI 1032Å (red) and CIV 1548Å (green) calculated from the ionization, density, temperature and velocity profiles from the hydrodynamical simulation at $t = 4.0 \times 10^4$ yr. The CIV is concentrated in the forward shock and the reverse shock whereas the O VI comes mostly from the hot gas in the bubble. As a result the absorption profiles are markedly different and peak at different velocities.

Publications

“The Nature of the Vela Supernova Remnant as Revealed by O VI and C IV Absorption Lines”, Nichols, J., Slavin, J., & Anderson, C. 2001, AAS Meeting 1999, 126.12.

“Ultraviolet Absorption Line Study of the Vela Supernova Remnant”, Nichols, J. & Slavin, J. 2002, in preparation.

“FUSE Observations of Highly Ionized Gas in the Vela Supernova Remnant”, Slavin, J. & Nichols, J. 2002, in preparation. “The Frequency and Distribution of High Velocity Gas in the Galactic Plane”, Nichols, J., Slavin, J., & Anderson, C. 2002, in preparation.

